Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 10 September 2009 (MN LaTeX style file v2.2)

Further Searches for RRATs in the Parkes Multi-Beam Pulsar Survey

E. F. Keane[†1], D. A. Ludovici[3], R. P. Eatough[1], M. Kramer[1,2], A. G. Lyne[1], M. A. McLaughlin[3] & B. W. Stappers[1]

[†] *Enquiries to: ekean@jb.man.ac.uk*
[1] *University of Manchester, Jodrell Bank Centre for Astrophysics, Alan Turing Building, Oxford Road, Manchester M13 9PL, UK.*
[2] *Max Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany.*
[3] *Department of Physics, West Virginia University, Morgantown, WV 26506, USA.*

18 June 2009

ABSTRACT

We describe the steps involved in performing searches for sources of transient radio emission such as Rotating Radio Transients (RRATs), and present 10 new transient radio sources discovered in a re-analysis of the Parkes Multi-beam Pulsar Survey. Followup observations of each new source as well as one previously known source are also presented. The new sources suggest that the population of transient radio-emitting neutron stars, and hence the neutron star population in general, may be even larger than initially predicted. We highlight the importance of radio frequency interference excision for single-pulse searches. Also, we discuss some interesting properties of individual sources and consider the difficulties involved in precisely defining a RRAT and determining where they fit in with the other known classes of neutron stars.

Key words: stars:neutron – pulsars: general – Galaxy: stellar content

1 INTRODUCTION

Rotating Radio Transients (RRATs from herein) were discovered in a search of archival data from the Parkes Multibeam Pulsar Survey (PMPS from herein) by McLaughlin et al. (2006). These sources exhibit infrequent, short, relatively bright bursts of radio emission. The pulses have peak flux densities (at 1.4 GHz) ranging from ~ 100 mJy up to ~ 10 Jy and pulse widths in the range $2-30$ ms. As we detect pulses only occasionally from RRATs they are generally not detected in Fourier domain searches (although see discussion in section 3) but rather by searching for individual bright pulses (McLaughlin & Cordes 2003; Cordes & McLaughlin 2003). Periodicities can be determined by factorising the difference between each pair of pulse arrival times (as discussed in Section 2). The underlying periodicities are in the range $0.7-6.7$ s. These periodicities are believed to be spin periods and thus RRATs seem to be a new population of neutron stars. Further evidence for this comes from X-ray observations of RRAT J1819$-$1458 (the most prolific, brightest and thus well studied source) which have revealed thermal emission consistent with that expected from cooling neutron stars as well as an X-ray period identical to that determined from radio observations (Reynolds et al. 2006; McLaughlin et al. 2007).

We see these millisecond bursts as infrequently as once per hour and up to as often as every few minutes. The long periods observed are more comparable to the magnetars (Woods & Thompson 2006) and the Isolated Neutron Stars (INSs, aka XDINSs, Kaplan (2008)), than the radio pulsars and the relationship between these populations is an open question. The narrow pulse widths are comparable to individual pulses from radio pulsars. Coupled to their longer periods the duty cycles are apparently much smaller, but including the entire phase range wherein we see emission gives duty cycles comparable to integrated pulsar profiles, e.g J1819$-$1458 shows emission over $\sim 2.9\%$ phase range (Lyne et al. 2009). There have been many suggested explanations for the 'bursty' RRAT behaviour. Some assign it to detection issues with others favouring intrinsically transient emission. Weltevrede et al. (2006) support the former notion and suggest that the RRAT emission may be due to these sources being more-distant analogues of PSR B0656$-$14, i.e. pulsars whose regular emission may be below our detection limit but who show detectable giant pulses or have an amplitude distribution with a long tail at high flux densities. The alternative models view the emission as truly intermittent with the short duration bursts corresponding to activation times of external excitation events. This is the case in the model of Cordes and Shannon (2006) which considers the re-activation of inactive vacuum gaps due to the presence of circum-stellar asteroidal material. Similarly it has been proposed by Luo & Melrose (2007) that RRATs may be surrounded by a radiation belt which could stimu-

late transient emission in the magnetosphere. behaviour of RRAT

Apart from these unusual emission properties RRATs are also of interest due to the predicted size of the population, which is thought to be several times larger than the radio pulsar population (McLaughlin et al. 2006). Previously Keane & Kramer (2008) discussed the implications of such a large number of RRATs on the Galactic production rate of neutron stars. It was argued that the many classes of neutron stars now known do not seem to be accounted for by the Galactic core-collapse supernova rate. An evolutionary link between the neutron star classes might eliminate this birthrate problem. An alternative explanation would be that the population estimates for RRATs and other neutron star populations are hugely over-estimated.

The discovery of RRATs has sparked a renewed interest in time-domain searches for transient radio sources - a relatively unexplored parameter space (Cordes et al. 2004; Lazio et al. 2009) which will be revolutionised with upcoming instruments such as LOFAR (van Leeuwen & Stappers 2007), the ATA (e.g. van Leeuwen et al. 2009), the SKA pathfinders (e.g. Johnston et al. 2009), FAST (Nan et al. 2006; Smits et al. 2009) and eventually the SKA (Cordes et al. 2004; Smits et al. 2009). For now, addressing these questions requires improved population estimates and characterisation. In particular, we need to understand which potential selection effects are present during the discovery process and how they impact on the discovered population. With a better understanding of RRAT characteristics and the potential selection effects an improved population estimate for RRATs will be possible. Motivated by this we have performed a full re-processing of the PMPS searching for sources of single pulses of radio emission. In section 2 below we outline the steps involved in our re-processing. In Section 3 we discuss in some detail the observed characteristics of 10 newly discovered sources as well as the results of follow-up work on one detected, but previously known, source. For the purposes of sections 2 and 3 we will consider that for a source to be a RRAT at some frequency that it is necessary but not sufficient that it is detected more easily in a single pulse search than in a periodicity search. In section 4 we discuss in more detail a refined definition of what a RRAT is as well as the implications for the Galactic neutron star population of these new discoveries before concluding with an outlook towards surveys with LOFAR and the SKA.

2 PMSINGLE

In the original RRAT discovery paper (McLaughlin et al. 2006) it was estimated that approximately half of the RRATs visible in the PMPS had been detected, with the remainder obscured due to the effects of radio frequency interference (RFI). Recently it has become timely to reprocess the PMPS survey in search of these postulated sources as we have developed a new and effective RFI mitigation scheme (Eatough et al. 2009). Utilising the Jodrell Bank Pulsar Group's recently acquired 1400-processor HYDRA super-computer, the whole PMPS data set was reprocessed. Modified versions of the *Sigproc*[1] processing tools were used. In the following we refer to this project as the PMSingle process.

We note that the presence of RFI will make a search somewhat blind to sources with low dispersion measure (DM). The DM of a source at a distance L from Earth is

$$DM = \int_0^L n_{\rm e}(l)dl, \qquad (1)$$

where $n_{\rm e}(l)$ is the electron density at a distance l. RFI is terrestrial in origin and, not having traversed the inter-stellar medium, we expect it to have $DM = 0$.[2] However as RFI signals are typically very strong, in comparison to the relatively weak astrophysical signals of interest, they are seen with sufficient residual intensity to mask celestial signals to high DM values. Figure 1 shows an example of this 'low-DM blindness' due to the presence of strong terrestrial RFI. This of course means that searches can miss real, low-DM sources. Thus our sensitivity to the nearby Galactic volume may have been reduced due to the effects of RFI in the initial analysis.

Before proceeding with outlining the PMSingle reprocessing steps we note some survey and data specifications: The survey covered a strip along the Galactic plane with $|b| < 5^o$ and between $l = 260^0$ and $l = 50^o$. It consists of 3196×35-minute pointings at an observation frequency of 1.4 GHz using the Parkes 21-cm multi-beam receiver. This receiver has 13 beams which each receive orthogonal linear polarisation so that there are 41561 dual-polarisation beams in total. An analogue filterbank with 96×3 MHz channels was used with 250-μs sampling. Once the data were received both polarisation signals were added to give total intensity (Stokes I) and the data were 1-bit digitised before recording. Thus the raw data for each beam can be visualised as a 1-bit digitised data cube (time, frequency and amplitude). The survey specifics are described in more detail in Manchester et al. (2001).

Our PMSingle processing involved the following steps:

(i) *Remove all clipping algorithms.* In previous analyses of the PMPS the raw data have been 'clipped', i.e. the data were read in 48 KB blocks and those blocks wherein the sum of all the bit values was larger than some (user supplied) threshold above the mean had their values set to the mean level (half 1s and half 0s in the case of 1-bit data). The motivation for such clipping is that RFI signals are typically much stronger than real astrophysical signals, so that the brightest detections are taken to be RFI spikes. This, however, is not optimal in that it removes signals based on strength and the discovery of RRATs and pulsars which show strong single pulses show that such signals may be of astrophysical interest. The threshold used is also arbitrary and usually determined on a trial-and-error basis. We note that the strongest pulses with high dispersion (i.e. dispersed over 2 or more blocks) can escape being clipped in error so that low-DM sources are the most likely to be clipped in this way. We therefore removed this step from our re-processing.

[1] http://sigproc.sourceforge.net/

[2] RFI signals emerging from air-traffic control radar, a particular problem at frequencies near 1400 MHz, are sometimes observed to also show signals sweeping in frequency.

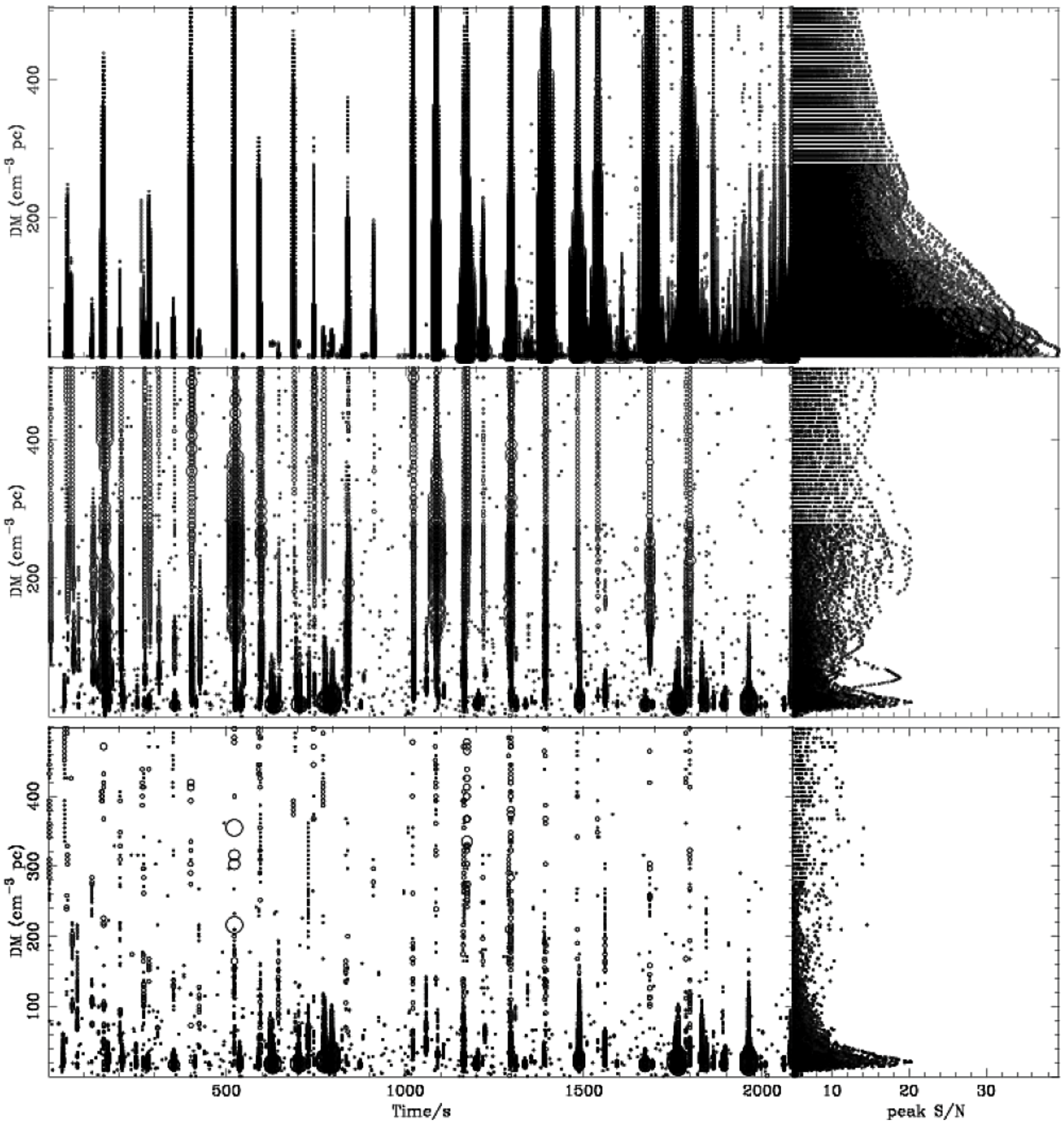

Figure 1. The ordinate in the large left-hand plots is trial DM over the range $0-500$ cm^{-3}pc and the abscissa is time over a 35-minute PMPS observation. To the right are plots of trial DM versus peak signal-to-noise ratio. Significant detected events are plotted as circles with radius proportional to signal-to-noise. (a) The strong vertical stripes across wide DM ranges are instances of extremely strong RFI. Inspection of the plot for the presence of a celestial source is impossible due to the presence of this RFI. (b) The same beam after the zero-DM filter has been applied (see §2(ii)). We can see that the RFI has not been completely removed, especially at higher DMs. However the RFI has been removed much more effectively at low DMs and a source at DM$\sim$ 20 cm^{-3}pc is beginning to become visible. (c) The same beam after application of the zero-DM filter and the removal of multiple-beam events. We can see that the diagnostic plot is cleaned up even further and, although there is still remnant RFI, it is clear that there is a real source in this beam at DM$\sim$ 20 cm^{-3}pc. This is the first detection of J1841$-$14 in the PMPS, the lowest DM source found so far in the survey.

(ii) *Dedisperse the raw filterbank data using the zero-DM filter.* We searched for dispersed signals in a DM range of $0-2200$ cm^{-3}.pc. For the Galactic longitudes covered by the PMPS this corresponds, at $|b| = 0^o$, to typical distances of $\gtrsim$ 40 kpc at $l = 260^0$ and $l = 50^o$ to 8.5 kpc towards the Galactic centre. The zero-DM filtering technique can be simply stated: for each time sample $t_{\rm j}$ we average all $N_{\rm chans}$ frequency channels and subtract this average from each channel. The value of a frequency channel $f_{\rm i}$ at time $t_{\rm j}$ is $S(f_{\rm i}, t_{\rm j})$ and after applying the zero-DM filter function will become:

$$\begin{aligned} S(f_{\rm i}, t_{\rm j}) &\rightarrow S'(f_{\rm i}, t_{\rm j}) \\ &= S(f_{\rm i}, t_{\rm j}) - \frac{1}{N_{\rm chans}} \sum_{i=1}^{N_{\rm chans}} S(f_{\rm i}, t_{\rm j}). \end{aligned} \quad (2)$$

This has the effect of removing short-duration broadband RFI but real dispersed pulses will be convolved with a particular function. After applying this filter we dedisperse the data. A dispersed input square pulse $\sqcap(t,{\rm DM}, w, BW, f_0)$ at time t, with pulse width w, observed with a bandwidth BW

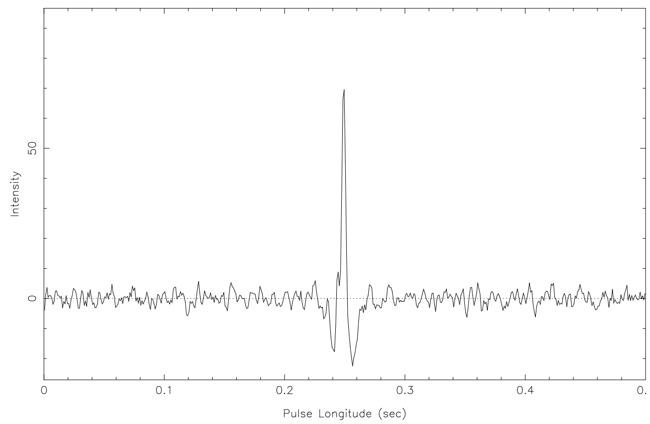

Figure 2. An example of a single pulse detected from J1841−14. Here we plot 0.5 seconds of the 6.6-second period centred on the pulse with intensity plotted in arbitrary units. Evident are the dips either side of the pulse which is a remnant of the zero-DM filtering process.

at a central frequency f_0 will become:

$$\sqcap(t, \mathrm{DM}, w, BW, f_0) \rightarrow \mathfrak{W}(t, \mathrm{DM}, w, BW, f_0) \\ = \sqcap(t, \mathrm{DM}, w, BW, f_0) - \triangledown(t, \mathrm{DM}, w, BW, f_0). \quad (3)$$

The peak of the pulse is reduced with the addition of triangular 'dips' either side of the pulse with the exact shape dependent on the pulse's DM and width, as well as on f_0 and BW. Examples of this are given in Figure 2 which shows single pulses detected from J1841−14. We note that the zero-DM filter acts as a more natural RFI mitigation tool than standard clipping as it removes signals based on their dispersion properties as opposed to sheer strength. Details of the zero-DM filter including assumptions, uses and limitations are discussed in detail in Eatough et al. (2009).

(iii) *Search for bright single pulses.* This is an excercise in matched filtering using box-cars of various sizes. However, instead of rectangular box-cars the zero-DM filtering means it is optimal to search with box-cars of the form $\mathfrak{W}(t, DM, w, BW, f_0)$ for various trial widths. That this is the optimal strategy is evident from examining the pulse in Figure 2 which clearly shows the characteristic dips from the zero-DM filtering procedure. In PMSingle we search for pulse widths as narrow as 250 μs to as wide as 128 ms at the lowest DMs. As we increase the DM trial value we get dispersive smearing of pulses to widths much longer than their intrinsic widths so at these DMs we search for even wider pulses. The widest pulse widths searched for are a factor of 16 larger than in the original PMPS single-pulse search analysis of McLaughlin (2009a).

(iv) *Perform a beam comparison to remove multi-beam events.* The zero-DM filtering is effective at removing short-duration broad-band RFI. The more persistant or narrow-band that RFI is the less likely it will be completely removed. However as the PMPS used a 13-beam receiver we have extra information to help with RFI mitigation. Pulsar signals are very weak and typically are seen in only one beam. The strongest pulsars (e.g. Vela) can be seen in a few beams but normally no more than three. Even the extremely bright 30-Jy 5-ms single burst (from an unknown source possibly at a cosmological distance) reported by Lorimer et al. (2007), was seen in just three beams. We can thus apply a rejection criteria for detected events like: for each detected event - $(DM, time)$ point, if we have detections in the range $(DM \pm \varepsilon_{DM}, time \pm \varepsilon_{time})$ for, e.g. $\geqslant 5$, beams in that pointing then ignore this detection as it is most likely RFI. We conservatively took ε to be one bin in each case (i.e. one DM trial step and one time sample step). In addition, for all beams, a check is made against the known pulsars (from the ATNF pulsar database[3], Manchester et al. (2005)) which fall within the beam.

Table 1. The classifications of the PMPS beams in the PMSingle single-pulse search. For the known sources the number of unique sources detected are given in parentheses.

Classification	$N_{\mathrm{detections}}$
Candidate:Class 1	162
Candidate:Class 2	204
Candidate:Class 3	319
Known PSR	606 (300)
Known RRAT	13 (11)
Noise	27493
Noise + some remnant RFI	12061
Large remnant RFI	693

(v) *Produce diagnostic plots for inspection and classification.* Along the lines of Cordes & McLaughlin (2003) a series of diagnostic plots are created for each beam. An example of this is shown in Figure 3. The plots include beam information (beam and pointing number, sky position etc.) as well as information on the number of multiple beam detections which were removed. Each beam was inspected and classified as containing either noise, known pulsars, known RRATs or new candidates - divided into Classes 1, 2 and 3. Examples of each of these classes are given in Figure 4. Class 1 candidates are all thought to be real sources, either yet-to-be confirmed RRATs or known pulsars detected in the telescope's far-side-lobes. Class 3 candidates are weak and no confirmations are expected. Class 2 sources are intermediate between these classes. Beams could also be classified as being too adversely affected with remnant RFI (not removed by zero-DM filtering or beam comparisons) so as to make inspection impossible. In these beams a real source, unless it were very strong, would not have been detectable. The results of the classifications are given in Table 1.

(vi) *Cross-check with known sources.* For each candidate we confirm that it is not a known pulsar (or RRAT). Even if there is no pulsar within the beam the pulses could still be from a known (strong) pulsar perhaps several beams away on the sky (e.g. PSRs B0835−41, B0833−45 and B1601−52 are detected many times like this). To do this we can compare the position (with a larger tolerance) and DM of the candidate to that of known sources.

(vii) *Determine a period for the candidate.* As RRATs are not seen in Fast Fourier Transform (FFT) searches (although see discussion in Section 3) we use a method of factorising the pulse time of arrival (TOA) differences to

[3] http:/www.atnf.csiro.au/research/pulsar/psrcat/

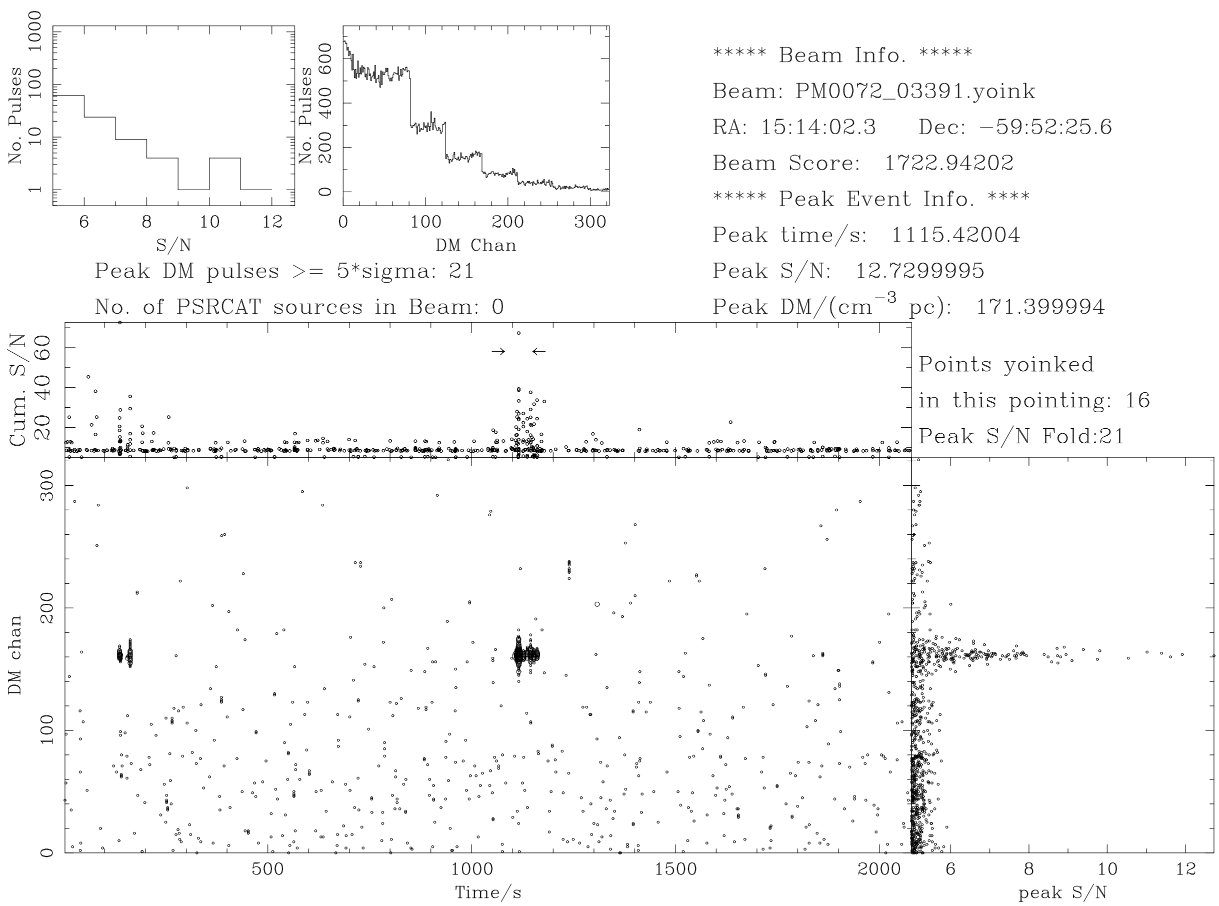

Figure 3. An example of the diagnostic plots. This plot shows the original detection of J1514-59. Two clumps of pulses are evident at ~ 150 s and at ~ 1100 s.

determine the period. For N TOAs there are at most[4] $(N/2)(N-1)$ unique TOA differences which we can use. For some small increment we step through a large range of trial periods. The correct period will fit all of the TOA differences with a small error and rms residual. Harmonics of the true period will also match many of the TOA differences but at a less significant level. If the most significantly matching period does not match all of the TOA differences then progressively removing the TOAs with the largest uncertainty will increase the significance of the match onto the true period. As a rule of thumb ~ 8 pulses (i.e. 28 TOA differences) in an observation allow a reliable period estimate, i.e. at the correct harmonic. We note that for a TOA difference to be usable in this method both pulses must not be far-separated so as not to lose coherence, e.g. 8 pulses in a single observation yields 28 usable TOA differences for period determination, but 2 separated observations each of 4 pulses yields just 12 TOA differences. Some example output plots from this method are shown in Figure 5. If a period determination is possible, it can be used with position and DM to further confirm whether or not the candidate is a previously known source. We note one difficulty with this method is that it is possible that the range of emitting pulse longitudes is wide (e.g. for an aligned rotator) so that sharp peaks like those shown in Figure 5 will be smeared out across a wider trial period range.

Table 3. Detection statistics for the confirmed sources from the PMSingle analysis. $\dot{\chi}$ refers to the detected burst rate.

Source	$N_{\rm det}/N_{\rm obs}$	$N_{\rm pulses}$	$T_{\rm obs}$ (hr)	$\dot{\chi}$ (hr^{-1})
J1047−58	8/15	54	8.96	6.0
J1423−56	9/12	35	10.01	3.4
J1514−59	9/9	92	4.58	20.0
J1554−52	8/8	214	4.25	50.3
J1703−38	5/6	10	3.08	3.2
J1707−44	5/5	22	2.58	8.5
J1724−35	12/17	34	9.95	3.4
J1727−29	2/5	2	2.11	0.9
J1807−25	7/7	25	3.97	6.2
J1841−14	13/13	231	5.01	46.0
J1854+03	9/9	42	4.52	9.2

[4] TOA differences can only be used if the TOAs are from the same observation as we quickly lose phase coherence of TOAs.

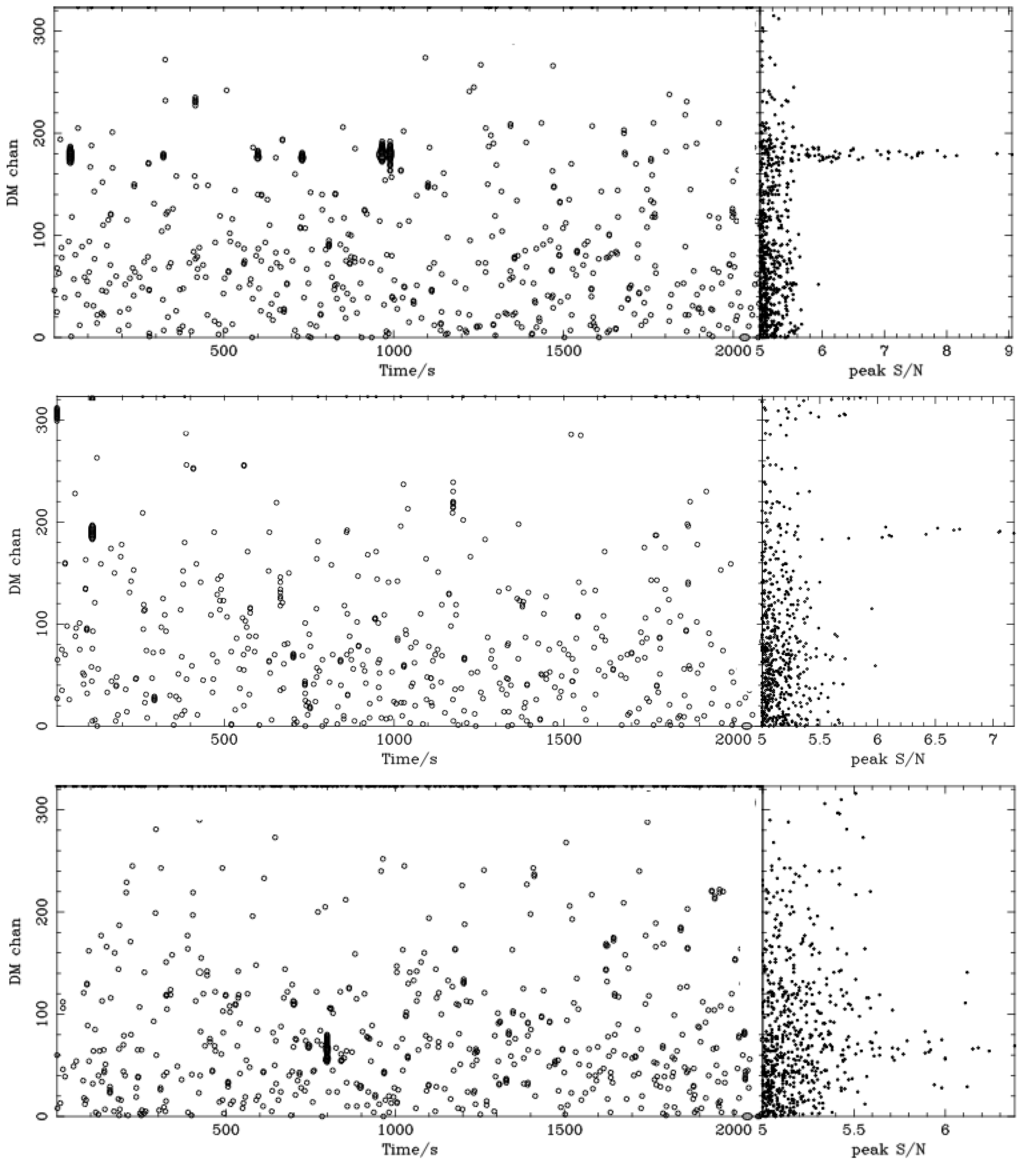

Figure 4. (Top) An as yet unconfirmed class 1 candidate with several strong pulses at constant DM which appears to be a real celestial source; (Middle) A class 2 source showing one significant pulse; (Bottom) A typical Class 3 candidates showing a weak single pulse. Class 3 sources are the least significant with no confirmations expected, especially due to the impractical nature of following up such weak sources.

3 INDIVIDUAL SOURCES

Currently we have confirmed 11 sources, 10 of which are new. These are listed in Table 2 with some observed properties. We note that these confirmed sources are amongst the better class 1 candidates. The detection statistics for these sources are given in Table 3. Coherent timing solutions have been obtained for all the sources that have determined periods, but spanning only a few months, so that accurate position and period derivative determinations are not yet possible. In this section we discuss the individual sources discovered in more detail.

Detection of Known Sources

In addition to the newly discovered sources the analysis has made many detections of previously known sources. These include detections of 300 previously known pulsars. Many of these were detected multiple times so that there were 606 known pulsar detections in total. Up to 2006 the PMPS detected 976 pulsars (of which, at the time, 742 were new sources, see for e.g. Lorimer et al. (2006)). Since then new analyses of results has given rise to more sources such that the ATNF pulsar database now lists 1030 pulsars as detected in the PMPS. The 300 known pulsar detections here then correspond to $\sim$ 30% of pulsars detected just from single pulse searches. This is an increase on the 250 pulsars detected in the original single pulse search (McLaughlin 2009a) with extra detections made across the entire DM range.

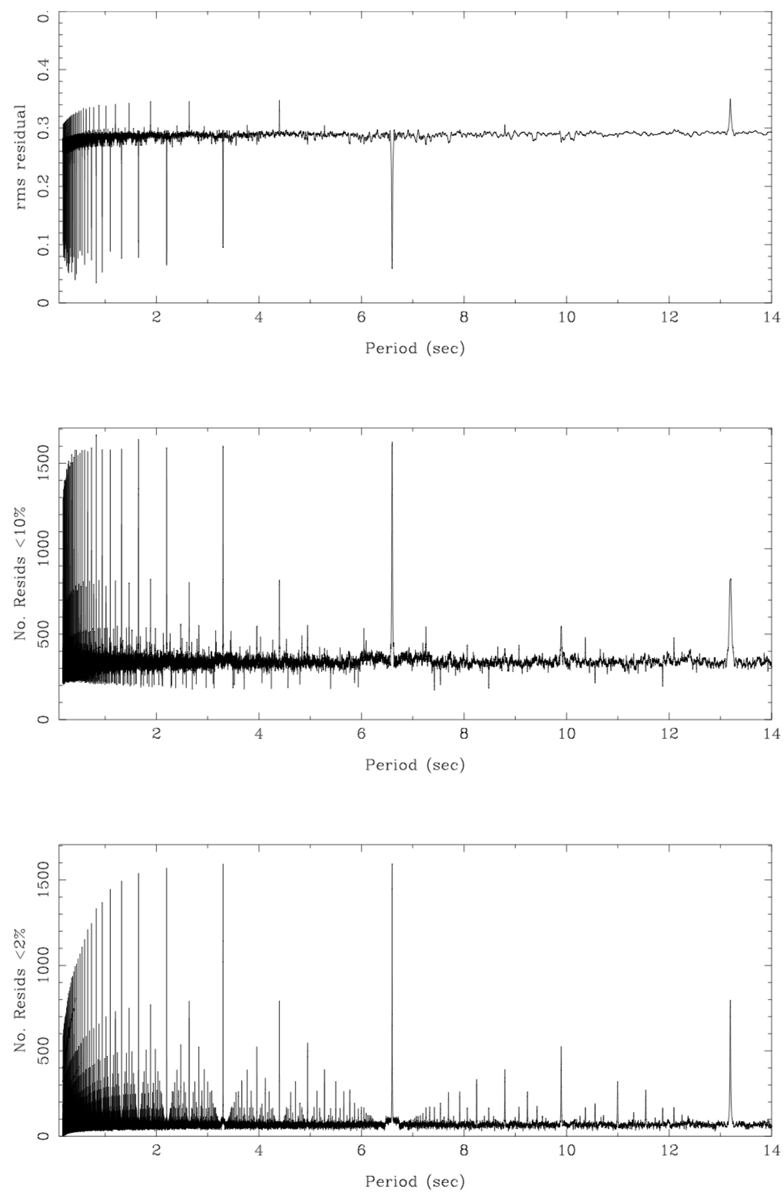

Figure 5. Trial period differences for J1841−14. The top panel shows the rms residuals for each trial period. The middle panel shows the number of rms residuals below 10% and the bottom panel shows the number with rms residuals below 2%.

The true PMSingle detection rate for known pulsar detections may even be better than 30% if we consider whether any of the pulsars detected in the PMPS would actually be removed by the zero-DM filter. This could be the case for low-DM pulsars. However, if we assume zero-DM must remove the amplitude spectrum up to a fluctuation frequency which is δ^{-1} harmonics in order to remove all information of the pulsar, where $\delta = w/P$ is the pulsar duty cycle, then just 4 of the PMPS pulsars would be removed. Assuming we need to remove just $P/2w$ harmonics would see 16 sources (or 1.6%) removed by the zero-DM filter which leaves the detection rate at $\sim$ 30%. In addition some of the sources classified as candidates may turn out to be (far side-lobe detections of) known pulsars which could potentially boost the number of single pulse detections by a few percent.

The original 11 RRATs were all re-detected. RRAT J1819−1458 is observed three times in the survey. The third PMPS detection, revealed in this analysis, was previously unknown. This is very helpful for timing and for attempts in connecting over a long $\sim$ 1800 day gap in timing data (between survey observations and the initial single pulse search of the data). This enables a conclusion that RRAT J1819−1458 does not seem to have suffered a large glitch during this gap in observations (Lyne et al. 2009).

Discussion of Interesting Individual Sources

J1047−58 was found within the same beam as the known pulsar J1048−5832. This allowed for a rapid confirmation of the source by examining archival Parkes data of the known pulsar. In the discovery observations, all of the six detected pulses were clustered within a $\sim$ 100 second window. In the

Table 2. The observed properties of the confirmed sources from the PMSingle analysis.

Source	RA (J2000)	DEC (J2000)	DM (cm^{-3}.pc)	D (kpc)	P (s)	Epoch (MJD)	w (ms)	S_{peak} (mJy)	L_{peak} (Jy.kpc^2)
J1047−58	10:47(1)	-58:41(7)	69.3(3.3)	2.3	1.23129(1)	55779	3.7	630	3.3
J1423−56	14:23(1)	-56:47(7)	32.9(1.1)	1.3	1.42721(7)	54557	4.5	930	1.5
J1514−59	15:14(1)	-59:52(7)	171.7(0.9)	3.1	1.046109(4)	54909	3.3	830	7.9
J1554−52	15:54(1)	-52:10(7)	130.8(0.3)	4.5	0.12522947(7)	54977	1.0	1400	28.3
J1703−38	17:03(1)	-38:12(7)	375.0(12.0)	5.7	-	-	9.0	160	5.1
J1707−44	17:07(1)	-44:12(7)	380.0(10.0)	6.7	5.763752(5)	54999	12.1	575	25.8
J1724−35	17:24(1)	-35:49(7)	554.9(9.9)	5.7	1.42199(2)	54776	5.9	180	5.8
J1727−29	17:27(1)	-29:59(7)	92.8(9.4)	1.7	-	-	7.2	160	0.4
J1807−25	18:07(1)	-25:55(7)	385.0(10.0)	7.4	2.76413(5)	54987	4.0	410	22.4
J1841−14	18:41(1)	-14:18(7)	19.4(1.4)	0.8	6.597547(4)	54909	2.6	1700	1.0
J1854+03	18:54:09(7)	+03:04(2)	192.4(5.2)	5.3	4.557818(6)	54909	15.8	540	15.1

In all sources except for 1854+03 we know the position to the accuracy of a 1.4-GHz beam of the 64-metre Parkes Telescope, which is 14 arcminutes. A more accurate position for J1854+03 is available from Deneva et al. (2008). The DMs given are those obtained from fitting the dispersion sweep of the brightest pulse for each source. The distances quoted are those derived from the DM using the NE2001 model (Cordes & Lazio 2002; Cordes & Lazio 2003) of the electron content of the Galaxy and have typical errors of 20 percent. The pulse widths are those measured at 50% intensity. The quoted 1.4-GHz peak flux densities are determined by using the radiometer equation (Lorimer & Kramer 2005) and using the known gain and system temperature of the 20-cm multi-beam receiver (as given in the April 6, 2009 version of the Parkes Radio Telescope Users Guide). The typical uncertainties in this calibration are at the 30 percent level.

followup observations of this source there is a suggestion of such 'on' times in which pulses are clustered together in windows of up to ~ 500 seconds.

J1514−59 is detected in all observations with a period of 1.046 seconds and a large average burst rate of $\dot{\chi} \sim 20\ \mathrm{hr}^{-1}$. It is not seen in FFT searches of entire observations which have all been ~ 30 minutes in duration. However its pulses are seen to come in approximately minute-long clumps separated by $\sim 800-1000$ seconds. Figure 3 shows an example of this. Performing FFT searches focused on a small 'on' region (albeit with quite poor spectral resolution of ~ 10 mHz) gives a period which agrees with that obtained from examining the differences in pulse pair arrival times. Folding the 'on' regions at the nominal period gives us a pulse profile which shows a single narrow peaked pulse.

Analysing the intervals between the bursts shows that they do not obey a Poission distribution. The K-S test probability that the distribution is Poissonian is $< 10^{-8}$. In fact it seems the distribution is bi-modal with a peak at short burst intervals (of a few periods) and another at long intervals (several hundred periods). We find that the short intervals are consistent with a Poissonian distribution with average expected interval of $\lambda = 7$ periods. More observations are needed to determine the 'peak' of the longer interval distribution.

The long ~ 15 minute intervals do not seem to be due to the effects of interstellar scintillation. For this observation frequency and DM we are in the strong scintilltion regime (Lorimer & Kramer 2005) and so must consider diffractive and refractive scintillation as possibilities. Assuming the NE2001 model (Cordes & Lazio 2002; Cordes & Lazio 2003) of the Galactic free electron density we find a diffractive time-scale Δt_{DISS} of ~ 30 seconds which is much too short to explain this modulation. Similarly the diffractive scintillation bandwidth Δf_{DISS} is just ~ 10 kHz, much narrower than the bandwidth of a single channel in any of these observations. Thus every channel averages many scintles and observing this modulation is not possible. The refractive scintillation timescale is related to the diffractive timescale by $\Delta t_{\mathrm{RISS}} = (f/\Delta f_{\mathrm{DISS}})\Delta t_{\mathrm{DISS}}$ which in this case is ~10s of days which is much too long to account for this modulation.

It would seem then that this modulation may be something intrinsic to the neutron star. The situation seems somewhat consistent with a nulling pulsar where the majority of the pulses emitted during the non-nulling phase are below our sensitivity threshold. This would imply a nulling length of ~ 14 minutes and a nulling cycle of ~ 1 minute, i.e. a nulling fraction of more than 90%. In studies of 23 nulling pulsars detected in the PMPS Wang et al. (2007) observed nulling fractions from as low as 1% to as high as 93%. One source showed a similar nulling cycle of ~ 515 seconds although most were lower. This is not inconsistent however due to the obvious difficulty of detecting long-duration nullers. Their results also showed large nulling fraction to be related to large characteristic age, $\tau = P/2\dot{P}$ rather than long periods, a relationship which can be tested for this source once a full timing solution has been obtained. We do note the similarity between J1514−59 (and J1047−58) and the class of "intermittent pulsars" (Kramer et al. 2006). However the time-scales for the 'on' and 'off' states in these sources can be 10s of days which is much longer than what is seen in these RRATs. The possibility remains though that RRATs may fit into a continuum of nulling behaviour which could range from those sources which null for a few periods at a time at one extreme to the intermittent pulsars at the other extreme. As the numbers of known RRATs and intermittent pulsars increases timing observations can be used to investigate what properties (if any, e.g. period and age) correlate with nulling fraction.

J1554−52 is a strong single pulse emitter showing 35 pulses in its discovery observation. It is also weakly detectable in FFT searches of most observations but with much higher significance in single pulse searches. The weakness

in the FFT detection is one reason for the previous non-detection of this source. However it is likely that this source would have been removed by previously applied algorithms designed to remove RFI signals. For instance frequency domain 'zapping' would have removed this source, i.e. setting certain frequencies in the fluctuation spectrum (of a dedispersed time series) to zero. This is done at known RFI frequencies (e.g. 50 Hz) and their harmonics. With a period of 125 ms this pulsar falls exactly into one of these zapped regions. The pulses are also seen to fall into two main phase windows, reminiscent of the three such windows observed in RRAT J1819−1458 (Lyne et al. 2009).

J1724−35 was the first source to be discovered in this re-processing (Eatough et al. 2009). Since the 2 survey observations of this source it has been re-observed 15 times and detected in 10 of those. Despite having a fairly high DM its discovery is helped immensely by the removal of very strong RFI by the zero-DM filter. In all but 2 observations it is not detected in an FFT search. In one observation it can be detected from focussed FFT searches of times when strong single pulses are seen, as for J1514−59. In another observation it is detected with FFT S/N of 15 which is evidence that there is underlying weak emission in addition to the detected single pulses. During these times when the source is detectable in periodicity searches a folded profile can be obtained which is quite wide and double-peaked. We note that this variation is not due to scintillation as the scintillation time-scale of 2 seconds is too short and the bandwidth of $\sim$ 20 Hz is too narrow to explain this. The burst rate is insufficient for analysis of the intervals between bursts at present.

J1727−29 is detected once in the PMPS with just one strong single pulse. It was re-observed in a followup observation where we again detected just one pulse. Further followup observations have not revealed anything further from this source. This source is obviously too weak to time and without even two pulses in a single observation a period estimate is not possible. We expect a number of candidates like this to be confirmed while proving impractical to continuously monitor. Such sources will require the next-generation sensitivity of the SKA and further serious followup efforts should be engaged when such facilities become available.

J1841−14 was observed twice in the PMPS where, as we can see from Figure 1, its detection was hindered by the presence of strong RFI in the initial analysis. The source has been re-observed 11 times and detected in all cases. It has the lowest DM of any RRAT found in the PMPS (and lower than 95% of normal radio pulsars). It has a very high burst rate of $\dot{\chi} \sim 40$ hr^{-1} but it is undetectable in an FFT search. However this seems to be due to the insensitivity of FFT searches in detecting long periods[5]. Using a Fast Folding Algorithm (Kondratiev et al. 2009), an alternative periodicity search, more sensitive than FFTs for high periods, we detect the source at the correct period. The average FFA S/N is 9 as compared to the peak single pulse S/N of $\sim$ 60 and many pulses per observation with single pulse S/N $\geqslant$ 15. It has a very long period of 6.596 seconds as determined from factorising the pulse pair time-of-arrival differences. Figure 5 shows the results of this period determination. Folding the observations at this period shows a narrow pulse profile. The pulses observed are among the brightest seen for RRATs with typical peak flux densities (at 1.4 GHz) of $\sim$ 1 Jy and a maximum peak flux density observed of 1.7 Jy. While most of the pulses are narrow at $\sim$ 2 ms there are few pulses detected with pulse widths of as wide as 20 ms. The high burst rate means that obtaining a sufficiently large number of TOAs at regular intervals to obtain a coherent timing solution should be straightforward. Obtaining an accurate timing position will be useful for a detection of this source at X-rays which appears very promising as the source is nearby at a distance of $\sim$ 800 pc.

J1854+03 was observed once in the PMPS and has since been re-observed eight times and detected in all cases. This source is one previously identified by the 1.4-GHz PALFA survey (Deneva et al. 2008). As the PALFA position is much more accurate than that which we were able to obtain with the Parkes telescope (due to the much smaller beam size of the Arecibo telescope) it may be possible to determine a period derivative for this source on a shorter timescale than for the other sources. This is because, typically, determining a period derivative takes a year of timing observations so that the effects of positional uncertainty (which shows year-long sinusoidal patterns in timing residuals) and the slow-down rate of the star can be disentangled. This source has a high burst rate which is $\dot{\chi} \sim 10$ hr^{-1}. It is undetectable in FFT searches and has a long period of 4.558 seconds. However this more distant source (it is $\sim$ 6 times further away than J1841−14) shows weak pulses. Typical peak flux densities (at 1.4 GHz) are $\sim$ 100 mJy but the brightest observed pulse is $\sim$ 540 mJy. The pulse widths are typically $\sim$ 15 ms and there are no indications of clumps of emission on which to focus FFT searches.

4 DISCUSSION

The motivation for this re-processing of the PMPS is to find more RRAT sources. The reason for this is that the RRATs seem to represent a very large population of Galactic neutron stars, likely larger than the regular radio pulsar population. It is therefore important to clearly describe differences between RRATs and pulsars, leading to a meaningful definition of RRATs. Having discovered the existence of RRATs by their bursty emission, our on-going studies of their emission properties suggests that a useful definition will go beyond a simple description of this burst behaviour.

What is a RRAT?

From a detection point of view it is difficult to define a RRAT. One possible definition is that of a source only detectable in single pulse searches and not in periodicity searches. As the RRATs seem to have intrinsically longer periods one might think this is a selection effect. For equal amplitude distributions one might indeed expect less periodicity search detections as the number of pulse periods in a given observation time is less. However McLaughlin et al. (2009b) show that the period distributions are different with high significance and that the single pulse search sensitivity does not select against low-period RRATs should they exist.

[5] This is due to red-noise and in the case of the zero-DM filter a suppressed fluctuation spectrum at low frequencies

It seems therefore that the RRATs have intrinsically longer periods than most radio pulsars.

One might extend the definition to be that of a source more easily detected in single pulse searches than periodicity searches. The so-called "intermittency ratio", R, is defined as the ratio of the single pulse and periodicity search S/N ratios. Thus a RRAT would be considered to be a source that has $R > 1$ but this immediately has several problems as the intermittency ratio varies between observations and some kind of arbitrarily averaged value of R would be needed. Also, as far as detectability is concerned several single pulses with, say, S/N of 10 are much more easily detectable than a periodicity search with a similar S/N of 10 due to the different false-positive noise levels for each method. Thus the same value of R can describe very different scenarios and its usefullness as a measure of detectability is limited. Another problem is that our current data suggest that a RRAT detected at 1.4 GHz can behave differently at a different observing frequency. Corresponding studies of the yet unknown spectra through multi-frequency observations of RRATs are underway (Keane et al. in prep; Miller et al. in prep.).

A detailed definition of RRATs therefore needs to include all of this information - intermittency, amplitude and spectral distributions, multi-frequency behaviour as well as period and period derivative properties and the derived quantities related to these in particular. For example, the inferred magnetic fields distribution in RRATs has been shown to be different to that of the pulsars with a high significance (McLaughlin et al. 2009b). In addition one source has also shown anomolous glitch activity (Lyne et al. 2009) although it is unknown whether this is characteristic of the entire population of RRATs. In Table 4 we summarise the observed properties of pulsars, magnetars, and the RRATs. The INSs are also likely to fit into the overal picture of how these neutron star classes are related but are not included here for lack of information on their radio properties. Further observations will constrain the ranges of these properties further for RRATs which will allow us to refine the classification of RRAT sources.

Distant Pulsars?

Closely related to the question of the nature of a RRATs are of course models that explain RRATs as distant analogues of pulsars with a pulse amplitude distribution with a long tail. Weltevrede et al. (2006) have shown that the nearby PSR B0656+14 (at a distance of 288 pc) would appear RRAT-like if moved to typical RRAT distances. The amplitude distribution of the pulses from this source are log-normal but can be described by a power law with index of between −2 and −3 at the high flux density end. We can test this scenario if we assume that RRATs emit pulses according to a power law amplitude probability distribution like

$$P \propto S^{-\alpha} \tag{4}$$

between flux density values $S_{\rm min}$ and $S_{\rm max}$. We detect all pulses above $S_{\rm thresh}$ where $S_{\rm min} \leqslant S_{\rm thresh} \leqslant S_{\rm max}$. This means that the fraction of observable pulses, g, is given by

$$g = \frac{\int_{S_{\rm thresh}}^{S_{\rm max}} P(S)dS}{\int_{S_{\rm min}}^{S_{\rm max}} P(S)dS} \tag{5}$$

where $S_{\rm max}$, $S_{\rm thresh}$ and g are all known. The observed values for g for the 9 new sources with known periods[6] are given in Table 5. Thus for various chosen power law indices α, we can determine $S_{\rm min}$. This can be used to determine the distance where we would need to move the RRAT to see all of its pulses (i.e. observe it like a pulsar which emits continuously with $g = 1$) from $D_{\rm new} = D(S_{\rm min}/S_{\rm thresh})^{1/2}$ by noting $L = SD^2$ where L, the radio luminosity[7], is the more intrinsic quantity.

Table 5 shows the distances one would need to move the sources discussed here to see continuous emission if they would be regular pulsars with amplitude distributions that follow power-laws. We can see that for the steepest power laws the source is not required to move very much nearer for all pulses to become visible. As the power law index gets shallower the source must be brought ever closer to be seen as a continuous emitter. For $\alpha \lesssim 1.5$ the change in distance becomes unreasonable such that if all RRATs were continously emitting pulses with energy distributions as a power law with $\alpha \lesssim 1.5$, almost none of these sources would ever appear as continuous emitters for a reasonable distance distribution and such sources would be seen as distinct from pulsars. We thus conclude that RRAT emission could be explained as coming from distant pulsars, i.e. continuous emitters, with steep power-law distributions only. For shallower pulse distributions a power-law alone cannot explain the observed RRAT emission as being due to distant pulsars. However the sources may still be seen as continuous if the distribution were to break to, e.g., a log-normal distribution at low flux densities. We can compare these results with the amplitude distributions from the initial RRAT discovery paper which showed some distributions being consistent with power law indices of $\alpha = 1$ (McLaughlin et al. 2006). Clearly, the amplitude distribution of pulses will provide a powerful discriminator between sources that can be explained as distant pulsars and those which cannot.

Figure 6 shows the amplitude distributions for J1514−59, J1554−52 and J1841−14, the three sources discussed here with the highest number of detected pulses. These distributions are found not to be consistent with a power-law distribution but instead are well fitted by log-normal distributions, the parameters of which are given in Table 6. The best-fit curves are over-plotted on the observed distributions in Figure 6. For these three sources there is a low flux density turn-over. It is not clear whether this is an intrinsic turn-over or simply due to the sensitivity threshold. The flux density threshold for a single pulse depends on the pulse width. Plugging in the known observing parameters for Parkes into the radiometer equation gives a single pulse peak flux of: $S_{\rm peak} \approx 245~{\rm mJy}({\rm w/ms})^{-\frac{1}{2}}$ assuming a 5-sigma detection threshold. Although the widths of the pulses vary from pulse to pulse we can take the average widths from Table 2 to get sensitivity estimates of 135 mJy, 250 mJy and 150 mJy for J1514−59, J1554−52 and J1841−14 respectively. If the turn-overs were intrinsic to the sources then it would suggest that we are not just seeing the brightest pulses from a continuously emitting source but rather that

[6] To determine g the period must be known as g is the average number of pulses per period, or $g = (\dot{\chi}/hr^{-1})(P/s*3600)$
[7] L has units of Jy.kpc^2 or equivalently W.Hz^{-1}

Table 4. Observed characteristics of (non-recyled) pulsars, magnetars and RRATs. Information in this table is taken from many sources: in addition to those references mentioned in the main text these include Camilo et al. (2006, 2007, 2008); Karastergiou et al. (2009); Lazaridis et al. (2008); Maron et al. (2000); McLaughlin et al. (2009b); Serylak et al. (2009) and the McGill Magnetar Catalogue http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html. $B_{\rm LC}$ and $B_{\rm S}$ refer to the inferred magnetic fields at the light cylinder and stellar surface respectively assuming a star with a dipolar magnetic field (see e.g. Lorimer & Kramer (2005). $B_{\rm quantum}$ is the quantum-critical magnetic field above which the separation of Landau levels for synchrotron orbits exceeds the electron rest mass. The quantities L, V and I refer to linear polarisation, circular polarisation and total intensity respectively. We note that although there are 29 published RRAT sources there are determined periods for just 27 and spin-down properties like $\dot{P}$, $B_{\rm S}$, $\dot{E}$ and τ are known for just 7 sources (McLaughlin et al. 2009b).

Property	Pulsar ($\sim$ 1700 sources)	Magnetar (18 sources)	RRAT (29 sources)
Period (s) [range,median]	$\sim 0.03 - 8.5$, 0.54	$2.1 - 11.8$, 7.3	$0.1 - 6.7$, 2.1
log(Period derivative)	-17 to -12	-13 to -9 (14 measured)	-15 to -13 (7 measured)
log($\dot{E}$) (erg/s)	$30 - 38$	$31 - 35$	$31 - 33$
log($B_{\rm S}$) (gauss) [range,median]	$10.0 - 14.0$, 12.03	$13.0 - 15.0$, $14.5 > B_{\rm Quantum}$ limit	$12.4 - 13.7$, 13.0
log($B_{\rm LC}$) (gauss)	-2 to 6	~ -0.01 to 1.1	~ -0.1 to 1.7
log($\tau = \dot{P}/2P$) (yr)	$3 - 9$	$2 - 6$	$5 - 6$
Observed Radio on-fraction	$0.05 - 1$	$0 - 1$	$10^{-3} - 10^{-2}$
Transient behaviour	nulls, intermittent PSRs	X-ray and radio variability	$\dot{\chi} \sim 1$ min^{-1} to ~ 1 hr^{-1}
Bursting behaviour	GRPs, giant micro-pulses, nano-giant pulses	X-ray and soft γ-ray bursts	$\lesssim 10$ Jy single pulses
No. of components/subpulses	$\geqslant 1$ components	large phase range, many components in XTE 1810$-$197	$\geqslant 1$ components $\geqslant 1$
Beaming fraction ($f_{\rm beam}(P)$)	$0.09[\log(P/s) - 1]^2 + 0.03$	unknown	unknown
Amplitude distribution	GRP: gaussian + power law, indices -1.5 to -4	power-law or log-normal, depending on which component	some log-normal (see §4), some power law, index -1
Radio spectra	$\nu^{-\alpha}$, $\langle\alpha\rangle = 1.8 \pm 0.2$	flat but variable	unknown
X-ray spectra	thermal and/or power-law	thermal + power law	thermal in J1819$-$1458
Polarisation	low $-$ high	$\lesssim 100$ percent	$L/I \sim 0.37$, $V/I \sim 0.06$ for J1819$-$1458

Table 5. The required distances to see continuous emission if these sources emit according to various power laws.

Source	g	D (kpc)	$g = 1$ distances (kpc)			
			($\alpha = 1.5$)	($\alpha = 2$)	($\alpha = 3$)	($\alpha = 4$)
J1047$-$58	0.0021(1/476)	2.3	0.01	0.12	0.50	0.83
J1423$-$56	0.0014(1/714)	1.3	< 0.1	0.05	0.25	0.43
J1514$-$59	0.0058(1/172)	3.1	0.03	0.26	0.86	1.31
J1554$-$52	0.0016(1/625)	4.5	0.01	0.20	0.91	1.54
J1703$-$38	-	5.7	-	-	-	-
J1707$-$44	0.0137(1/73)	6.7	0.14	0.84	2.30	3.28
J1724$-$35	0.0013(1/769)	5.7	0.03	0.30	1.18	1.94
J1727$-$29	-	1.7	-	-	-	-
J1807$-$25	0.0048(1/208)	7.4	0.61	2.00	3.05	
J1841$-$14	0.0845(1/11.8)	0.8	0.10	0.24	0.43	0.53
J1854+03	0.0118(1/85)	5.3	0.10	0.61	1.75	2.53

we are seeing most pulses which are emitted. If this is the case, the bursty behaviour is indeed due to the lack of continuous emission and an innate property of the sources. For the remaining sources the number of pulses detected is as yet still too low for such an analysis. Continued observations will allow accurate determination of amplitude distributions of all the sources as more observations are made.

The Emerging RRAT Population

We note that the scope of any definition can and should be wary of those radio pulsars which are sufficiently weak and/or distant not to be detected by periodicity searches. Such sources are automatically accounted for by the predicted Galactic pulsar population. For instance there are estimated to be $\sim$ 150,000 radio pulsars in our Galaxy with a radio luminosity $L = SD^2 > 0.1$ mJy.kpc^2 (Lorimer et al. 2006), or $\sim$ 100,000 with $L > 1.0$ mJy.kpc^2 (Vranesevic et al. 2004). These estimates are arrived at from accounting for known observational selection effects of surveys and extrapolating from the observed properties of pulsars (e.g. the observed luminosity distribution and empirical beaming models). However we note that if the population of RRATs is indeed a factor of a few times larger than that of the radio pulsars not all RRATs can be accounted for as weak and/or distant pulsars. With the ad-

Table 6. The best-fit parameters to the amplitude distributions in Figure 6 for a log-normal probability density distribution of the form: $P(x) = (a/x)\exp[-\frac{(\ln x - b)^2}{2c^2}]$. The parameter a is an arbitrary scaling factor and the values given here correspond to the scales used in Figure 6.

Source	a	b	c
J1514−14	7613(748)	5.57(0.03)	0.47(0.03)
J1554−52	15662(1182)	6.13(0.03)	0.53(0.03)
J1841−14	16130(1704)	5.86(0.04)	0.53(0.04)

dition of these 11 new PMPS RRAT sources there are now 22 confirmed RRAT sources in the survey. There are a further 6 single pulse sources in the literature recently reported by (Deneva et al. 2008) (although some of these are detectable in FFT searches also) and one source discovered in the GBT350 survey (Hessels et al. 2007). Of these 29 currently known sources 27 have determined periods and seven (of the original 11) sources now have known period derivatives (McLaughlin et al. 2009b). The initial RRAT population estimate suggested that there were ~ 4 times as many RRATs as pulsars (McLaughlin et al. 2006). We defer a complete population analysis until we have investigated all of our best candidates but we can already comment on some of the selection effects impacting upon this estimate. These include the RRAT beaming fraction, their observed on-off fraction and the fraction missed due to contaminating RFI: (a) With no reliable information on a beaming model for RRATs, we continue to use the empirical pulsar beaming model, $f_{\rm beam}(P) = 0.09[\log(P/s) - 1]^2 + 0.03$, of Tauris & Manchester (1998). Still, it remains to be seen what the actual RRAT beaming model might be or whether this beaming model even still applies for pulsars with long periods. The latter is highlighted by the recent discovery of a slow pulsar with an extremely narrow pulse by Keith et al. (2008). If beaming fractions were in fact overestimated, the projected populations of both pulsars and RRATs may be much larger. (b) The assumed averaged on-off fraction during a PMPS observation was taken to be 1/2, i.e. half of the RRATs that exist were assumed not to emit pulses during the 35 min observation which was consistent with the observed burst rates at the time. With the discovery and continued monitoring of a growing population of known RRATs it will be possible to determine the true burst rate distribution and thus to improve this value in population estimates. (c) The factor used to compensate for those sources missed due to the presence of RFI was quite uncertain and taken to be 0.5. Taking into consideration the pointings with strong residual RFI and the fraction of sources removed by zero-DM in the light of the PMSingle analysis the number of beams still affected by RFI is $(41561 - 693) * 0.016 + 693$ which is $\sim 3\%$ of all beams, so that 97% are now cleaned of RFI. We have doubled the number of known RRATs while simultaneously reducing the fraction missed by RFI to almost zero. The inferred population estimate is thus related to the initial estimate by a factor of $(97/50)/2 \approx 1$ so that the confirmed number of new sources is consistent with the original population estimate (McLaughlin et al. 2006). However, if even a small fraction of the large number of other candidates are confirmed as new RRATs, the initial population estimate will need to be revised upwards so that the number of transient radio emitting neutron stars in the Galaxy is even larger than initially thought. Of course with the continued monitoring and thus characterisation of more sources we can also improve our knowledge of the other selection effects.

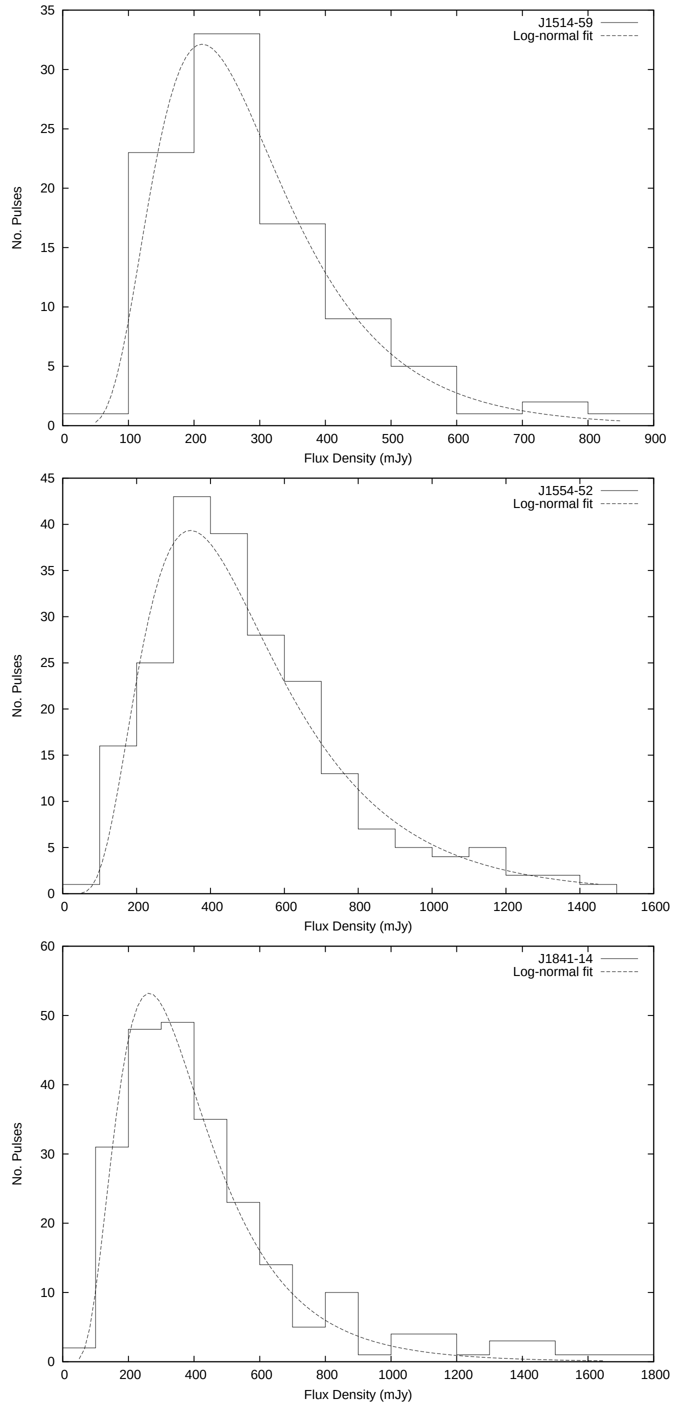

Figure 6. Amplitude distributions for: (Top) J1514-59; (Middle) J1554-52 and; (Bottom) J1841-14.

Assuming the population of RRATs is indeed much larger than that of the normal radio pulsars, the neutron star birthrate problem remains. In addition to pulsars and

RRATs there are the INSs, magnetars, neutron stars in accreting binary systems and the Central Compact Objects (of which some are thought to be neutron stars, e.g. see de Luca (2008)). Kondratiev et al. (2009) suggest that more than 30 new INS sources need to be discovered before unfavourable beaming can be ruled out, i.e. that these sources are pulsars and/or RRATs whose beams do not cross our line of sight. Recently several tens of new INS candidates have been identified (Pires et al. 2009) so that progress may come in this area despite the difficulty in finding such sources (Posselt et al. 2008). Besides pulsars many more sources are needed for the other classes to reach a conclusive answer as to the links (if any) between these populations.

5 CONCLUSIONS

We have presented an overview of the steps involved in performing searches for sources showing single pulses of radio emission. These have enabled us to discover 11 new PMPS sources from which between 2 and 231 pulses have been detected. Underlying periodicities for these sources lie in the range of 125 ms up to 6.6 s. These join the original 11 RRAT sources identified previously in the survey. We have reduced the uncertainties with regard to the number of sources missed due to the contaminating effects of RFI. The projected population of these sources still appears to be larger than the regular radio pulsars. However we are yet to determine the burst rate and beaming distributions for the RRATs - key ingredients in a complete population synthesis. These characteristics will be determined with continued monitoring of the new sources and followup investigations of the other promising candidates (of which there are now more than 100). It seems also that there will be many candidates for whom it will be impractical or impossible to follow up at present with current observing facilities. These will require followup with instruments like LOFAR, FAST or the SKA. We note that these these instruments will produce extraordinarily large volumes of data so that searching for transient RRAT-like sources will necessitate the development of automated algorithms which will use the steps as outlined above.

ACKNOWLEDGMENTS

We would like to thank the anonymous referees for providing helpful comments which have improved the quality of this work. EK acknowledges the support of a Marie-Curie EST Fellowship with the FP6 Network "ESTRELA" under contract number MEST-CT-2005-19669. MAM is supported by a WV EPSCoR grant.

REFERENCES

Camilo F., Ransom S. M., Halpern J. P., Reynolds J., Helfand D. J., Zimmerman N., Sarkissian J., 2006, Nature, 442, 892

Camilo F., Reynolds J., Johnston S., Halpern J. P., Ransom S. M., 2008, ApJ, 681

Camilo F., Reynolds J., Johnston S., Halpern J. P., Ransom S. M., van Straten W., 2007, ApJ, 659, L37

Cordes J. M., Kramer M., Lazio T. J. W., Stappers B. W., Backer D. C., Johnston S., 2004, New Astr., 48, 1413

Cordes J. M., Lazio T. J. W., 2002, e-print (astro-ph/0207156)

Cordes J. M., Lazio T. J. W., 2003, e-print (astro-ph/0301598)

Cordes J. M., Lazio T. J. W., McLaughlin M. A., 2004, New Astronomy Review, 48, 1459

Cordes J. M., Shannon R. M., 2008, ApJ, 682, 1152

Cordes J. M., McLaughlin M. A., 2003, ApJ, 596, 1142

Deneva J. S., Cordes J. M., McLaughlin M. A., et al., 2008, e-print (astro-ph/0811.2532)

Eatough R. P., Keane E. F., Lyne A. G., 2009, MNRAS, 395, 410

Hessels J. W. T., Ransom S. M., Kaspi V. M., Roberts M. S. E., Champion D. J., Stappers B. W., 2007, e-print (astro-ph/0710.1745)

Johnston S., Feain I. J., Gupta N., 2009, e-print (astro-ph/0903.4011)

Kaplan D. L., 2008, in AIPC Series, Vol. 968, Yuan Y.-F., Li X.-D., Lai D., ed, Astrophysics of Compact Objects, p. 129

Karastergiou A., Hotan A. W., van Straten W., McLaughlin M. A., Ord S. M., 2009, MNRAS, 396, 95 (astro-ph/0905.1250)

Keane E. F., Kramer M., 2008, MNRAS, 391, 2009 (astro-ph/0810.1512)

Kondratiev V. I., McLaughlin M. A., Lorimer D. R., Burgay M., Possenti A., Turolla R., Popov S. B., Zane S., 2009, ApJ in press, e-print (astro-ph/0907.0054)

Kramer M., Lyne A. G., O'Brien J. T., Jordan C. A., Lorimer D. R., 2006, Science, 312, 549

Lazaridis K., Jessner A., Kramer M., Stappers B. W., Lyne A. G., Jordan C. A., Serylak M., Zensus J. A., 2008, MNRAS, 390, 839

Lazio T. J. W., Bloom J. S., Bower G. C., Cordes J. M., Croft S., Hyman S., Law C., McLaughlin M. A., 2009, e-prints (astro-ph/0904.0633)

van Leeuwen J., Stappers B. W., 2007, e-print (astro-ph/0712.3826)

van Leeuwen J., ATA Team, 2009, e-print (astro-ph/0908.1175)

Lorimer D. R., Bailes M., McLaughlin M. A., Narkevic D. J., Crawford F., 2007, Science, 318, 777

Lorimer D. R., Faulkner, A. J., Lyne, A. G., et al., 2006, MNRAS, 372, 777

Lorimer D. R., Kramer M., 2005, Handbook of Pulsar Astronomy. Cambridge University Press

de Luca A., 2008, in AIPC Series, Vol. 983, Bassa C., Wang Z., Cumming A., Kaspi V. M., eds, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, p. 311

Luo Q., Melrose D., 2007, MNRAS, 378, 1481

Lyne A. G., McLaughlin M. A., Keane E. F., Kramer M., Espinoza C. M., Stappers B. W., Palliyaguru N. T., Miller J., 2009, MNRAS, in press, e-print (astro-ph/0909.1165)

Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993

Manchester R. N., Lyne, A. G., Camilo, F., et al., 2001, MNRAS, 328, 17

Maron O., Kijak J., Kramer M., Wielebinski R., 2000, A&AS, 147, 195

McLaughlin M. A., 2009, in ASSL, Vol. 357, Becker W., ed,

Recent Radio and X-ray Observations of Rotating Radio Transients, p. 41

McLaughlin M. A., Cordes J. M., 2003, ApJ, 596, 982

McLaughlin M. A., Lyne, A. G., Lorimer, D. R., et al., 2006, Nature, 439, 817

McLaughlin M. A. Rea, N., Gaensler, B. M., et al., 2007, ApJ, 670, 1307

McLaughlin M. A. Lyne A. G., Keane E. F., Kramer, M., Miller J. J., Lorimer D. R. Manchester R. N., 2009b, MNRAS, in press, e-print (astro-ph/0908.3813)

Nan R.-D., Wang Q.-M., Zhu L.-C., Zhu W.-B., Jin C.-J., Gan H.-Q., 2006, Chin. J. Atron. Astrophys., Suppl. 2, 6, 304

Pires A. M., Motch C., Janot-Pacheco E., 2009, A&A in press, e-print (astro-ph/0906.4966)

Posselt B., Popov S. B., Haberl F., Truemper J., Turolla R., Neuhaeuser R., 2008, A&A, 482, 617

Reynolds S., Borkowski K. J., Gaensler B. M., et al., 2006, ApJ, 639, L71

Serylak M., Stappers B. W., Weltevrede P., et al., 2009, MNRAS, 394, 295, e-print (astro-ph/0811.3829)

Smits R., Kramer M., Stappers B. W., Lorimer D. R., Cordes J. M., Faulkner A., 2009, A&A, in press, e-print (astro-ph/0811.0211)

Smits R., Lorimer, D. R., Kramer M., Manchester, R. N., Stappers B. W., Jin C. J., Nan R. D., Li, D. 2009, A&A, in press, e-print (astro-ph/0908.1689)

Tauris T. M., Manchester R. N., 1998, MNRAS, 298, 625

Vranesevic N., Manchester R. N., Lorimer D. R., et al., 2004, ApJ, 617, L139

Wang N., Manchester R. N., Johnston S., 2007, MNRAS, 377, 1383

Weltevrede P., Stappers B. W., Rankin J. M., Wright G. A. E., 2006, ApJ, 645, L149

Woods P. M., Thompson C., 2006, Lewin W. H. G., van der Klis M., eds, Soft gamma repeaters and anomolous X-ray pulsars: magnetar candidates. p. 547